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Impacts of plug-in hybrid electric vehicles on a residential transformer using stochastic and empirical analysis

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HIGHLIGHTS

- Catastrophic failure of distribution transformers due to PEV charging is unlikely.
- Uncontrolled Level 1 charging has little effect on transformer life time.
- Off-peak charging results in prolonged transformer life.
- Smart charging and load management is critical for high load factor transformers.
- PEV demand is manageable for transformer even if multiple vehicles exist.

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ABSTRACT

Plug-in electric vehicles (PEV) have been identified as an option that can reduce criteria pollutant and greenhouse gas emissions associated with the transportation sector. The electricity demand of one of these vehicles is comparable to that of a typical U.S. household and thus clustering of PEVs in a neighborhood might have adverse effects on the transformer and disruption of service. In this paper, the electricity demand of a neighborhood is modeled based on measured vehicle and household data. The electricity demand profile of the PEVs is modeled based on the vehicle type, arrival and departure times and the daily miles traveled, all taken from the National Household Travel Survey (NHTS). A thermal model is developed to calculate the hot spot temperature and loss of life of the transformer.

Results show that Level 1 charging has a small impact on the transformer aging and that only in one case, with Level 2 charging, the transformer might fail due to excessive temperatures. Overall addition of a significant number of PEVs is manageable for the transformer. The negative effects on the life time can be mitigated by properly designing the transformers and using smart charging scenarios.

1. Introduction

Concerns about greenhouse gas emissions and global climate change have led governments to put more stringent regulations in place to reduce emissions from both mobile and stationary sources. Power generation and transportation sectors are major contributors to GHG emissions in the state of California [1] and significant reduction in these sectors is required to meet the state's AB32 regulation [2].

Among various technologies, plug-in electric vehicles (PEV) have been identified as a feasible transportation option for the near future and may pave the way for longer term solutions such as fuel cell vehicles, better public transit, and mixed-use transit oriented development. These vehicles have various advantages including reduced liquid fuel usage, lowered criteria pollutant emissions resulting in better air quality, utilization of the generation capacity that is idle during off-peak hours, reduced GHG emissions, and providing a cheaper source of mobility than gasoline on a per mile basis [3,4]. Vehicle-to-grid (V2G) capability and the use of battery packs as storage for peak shaving and flattening the electricity demand curve have been extensively studied. Overcoming the technological barriers and with a smart communication link between the grid and vehicle, V2G can help improve the grid efficiency, stability, reliability, and maximize the intermittent renewable energy integration [5–11].

The majority of previous studies focus on the impact of PEVs on the generation side of the electricity grid [11–21], concluding that with the addition of PEVs with controlled charging, building new power generation infrastructure will not be required [17–21]. The impact of PEVs on the distribution grid has not been as rigorously

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Nomenclature

AAF	aging acceleration factor
EAF	equivalent aging factor
LOL %	loss of life percentage
K	load factor (ratio of the load to the rated load)
R	ratio of power loss at rated load to no load condition
τ_{oil}	oil time constant
τ_w	winding time constant
θ_{HST}	Winding's hot spot temperature (°C)
θ_{amb}	ambient temperature (°C)
$\Delta\theta_{oil}$	top oil's temperature rise over ambient (°C)
$\Delta\theta_{HST}$	Winding's temperature rise over oil (°C)
$\Delta\theta_{oil,R}$	Top oil's temperature rise over ambient at rated power (°C)
$\Delta\theta_{HST,R}$	Winding's temperature rise over oil at rated power (°C)

studied, mostly because it was believed that the number of these vehicles in a particular area would not be high enough to have a significant influence on the transmission or distribution grids. However, recent support of plug-in hybrid electric vehicles (PHEV) by the United States government, with a goal of having one million PHEVs on the road by 2015 [22] combined with the fact that clustering of these vehicles can occur in a particular neighborhood [23], hints that the impacts of these vehicles on the local grid might not be as far in the future as previously anticipated.

The addition of a PEV to a household can result in doubling the household electricity demand peak [24], and having a cluster of these vehicles on a distribution transformer can result in an increase in the transformer temperature, undesirable harmonics, and consequently loss of the transformer life. These effects depend on the charging profile, vehicle penetration, driving pattern, and time of charging of vehicles [25] with the key factor being the charging profile, voltage and power level [26]. The number of overloaded transformers will increase linearly as the penetration of PEVs increases [26].

Shao et al. [27] conducted a study including 5 homes with 2 PHEVs and showed that no scenario results in transformer overload except all charging at peak time with 220 V charging (Level 2). Mosheni et al. [28] conducted similar simulations and only in a small number of these simulations the transformer was overloaded with the addition of PHEVs. Other studies have been conducted to identify the possible effects of PEVs on power losses, power quality, service and residential transformers, and 3-phase primary lines [26,29,30]. One conclusion that seems to be common in most studies is that in order to operate a more reliable and economic grid, and to prevent transformer loss of life and outages, smart communication between the vehicle and the grid would be necessary [7,31–33].

In this paper, the electricity consumption of a neighborhood including ten houses in Southern California is simulated based on measured electricity consumption data. A virtual PHEV with a 60 km (40 miles) all electric range and charging characteristics of a Chevrolet Volt, is added to each household. The electricity required to fully charge each vehicle is calculated for each scenario using National Household Travel Survey (NHTS) data [34] which include the times each driver leaves in the morning and returns in the evening, and also travel distance such that the state of charge (SOC) of the battery when the driver returns home can be calculated. In order to study a case with more possible negative impacts on the transformer, each scenario is also conducted with a battery electric vehicle (BEV) with 160 km (100 miles) range and characteristics of a typical BEV; 0.193 kWh km^{-1} (0.31 kWh min^{-1}) (DC) consumption and 0.85 charging efficiency [35].

A suitable transformer is chosen based on the number of customers that it serves and also the peak demand. In this study, 37.5 and 50 kVA transformers are found to be most appropriate based on the analysis. The load on the distribution transformer serving this neighborhood is then calculated and the transformer hot spot temperature (HST) is modeled. The IEEE C57.91 standard [36] is used to calculate the transformer's loss of life based on the dynamic temperature calculations.

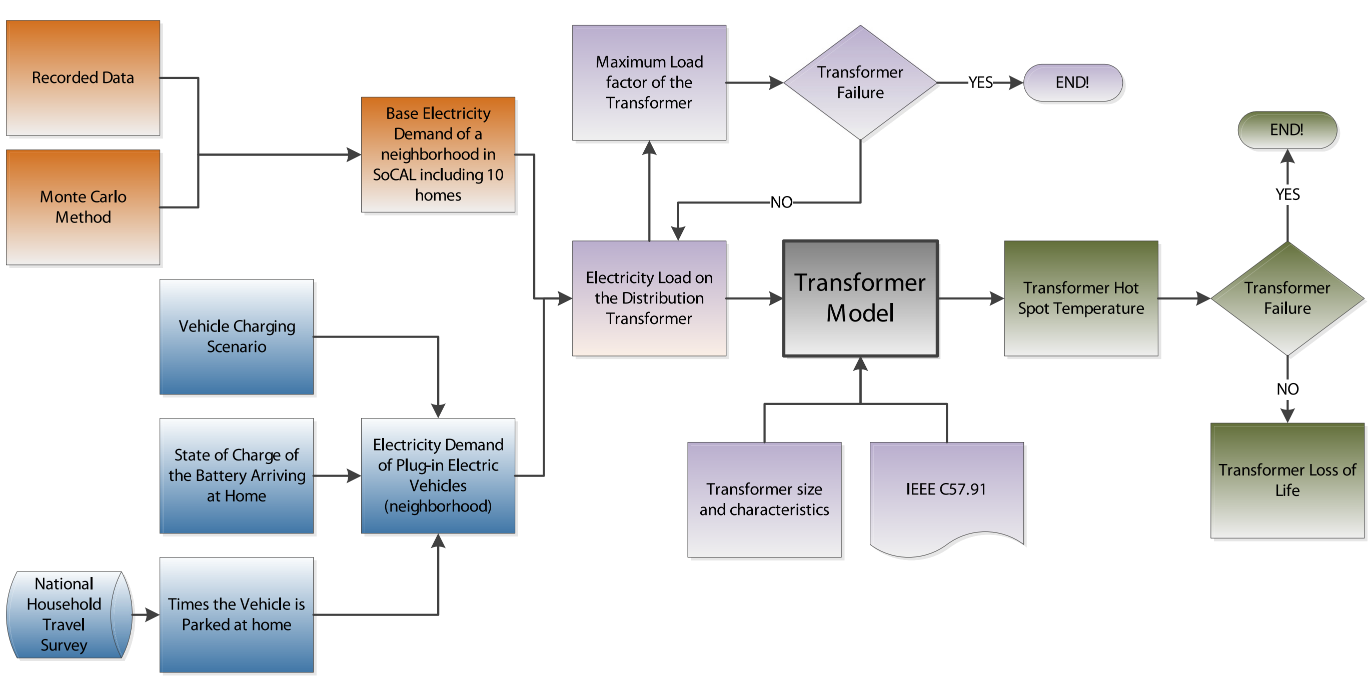

Fig. 1. Model flowchart.

The simulation is repeated several times to study the impacts of various charging strategies, charging level, and the transformer characteristics on the results. In Fig. 1 a flowchart of the model and process is depicted.

2. Methodology

2.1. Transformer load

The transformer load consists of the everyday electricity demand (*Basecase*) and the additional electricity that is required to charge the PEVs (PHEV or BEV). The *Basecase* electricity demand varies considerably from day to day and household to household and is affected by many factors. Simulating this electricity demand is complicated and requires using statistical tools. In this study, measured data are used as the basis of the statistical approach.

Electricity demand of a typical Southern California household was monitored every 15 s for the duration of two weeks. From the measured data and using stochastic methods (including Monte Carlo), ten electricity demand profiles were generated, each representing the electricity consumption of a household during a weekday. The apparent power (in VA) can be calculated using the real power and power factor which are monitored continuously. The demand profiles (kVA) are shown in Fig. 2 for each household for a weekday. The load on the distribution transformer is the sum of these ten houses. The transformer load for the *Basecase* (with no PEVs) is depicted in Fig. 3 with peak load on the transformer of 25.06 kVA.

To calculate the electricity demand of PHEVs, it is assumed that each household has a PHEV with an all-electric range of 60 km.

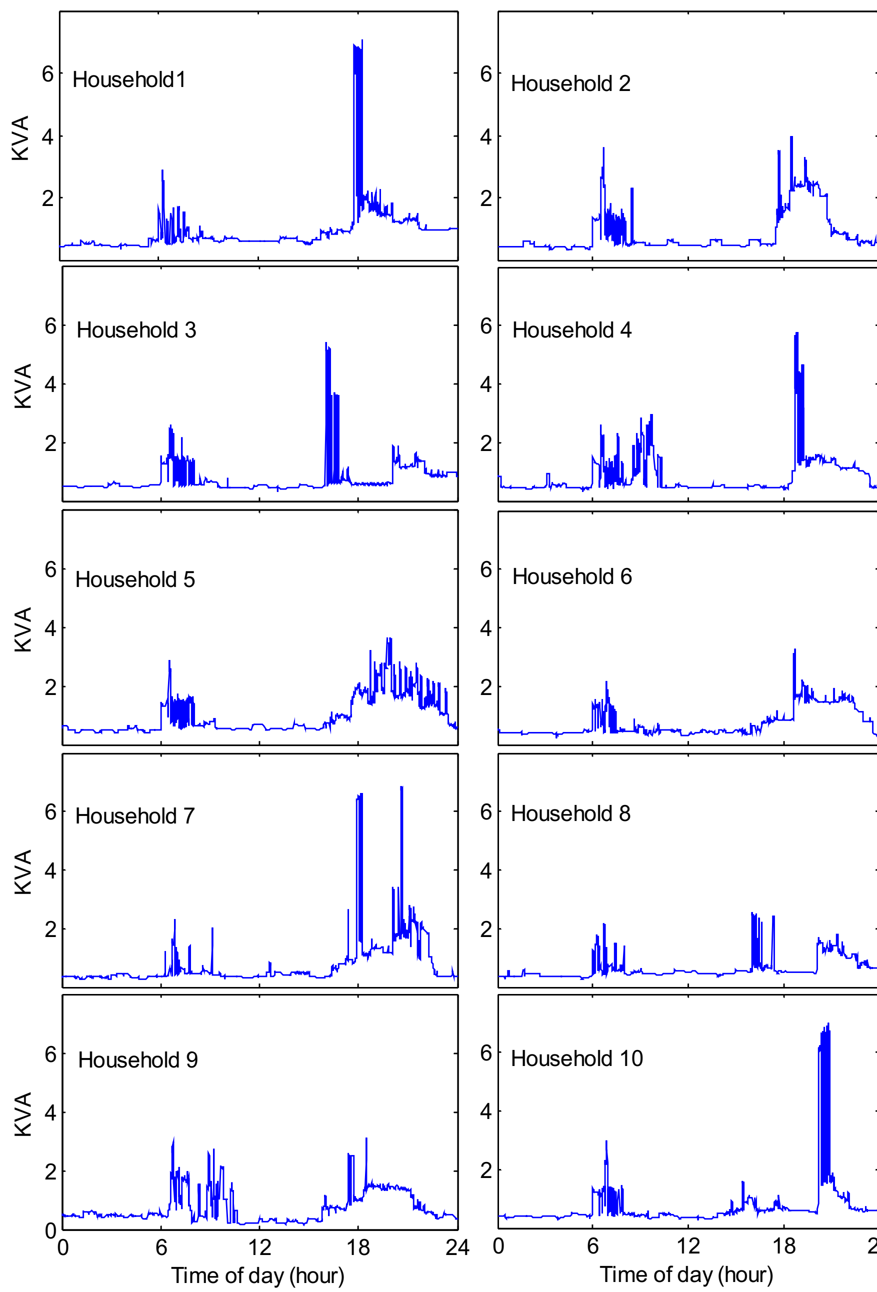

Fig. 2. Individual household apparent power (kVA) for the *Basecase*.

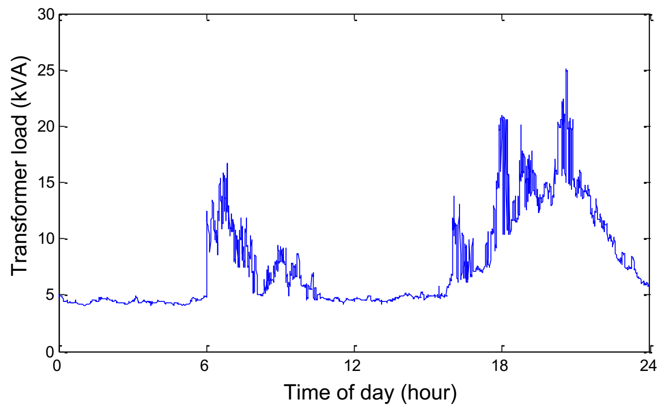

Fig. 3. Transformer load for the *Basecase*.

With an average of 2.2 vehicles per household in California [32] this results in a 45% penetration of these PHEVs which is consistent with the assumption that early PHEV adoption would be clustered in certain residential neighborhoods [23].

The National Household Travel Survey 2009 provides detailed driving patterns of participating drivers. These data include the times when the driver leaves the house and returns, and the state of charge of the battery can be modeled based on the driving pattern and behavior of the driver [4]. Ten drivers are chosen that statistically represent all those in Southern California that participated in the survey, meaning that the averages and standard deviations for the arrival and departure times, and miles traveled per day of these ten drivers are the same as those of the data collected from the entire Southern California. Arrival and departure times and the amount of electricity to fully charge the battery for these ten drivers are shown in Table 1. The reason why the electricity required to fully charge the batteries is the same for most cases is that the daily miles traveled is higher than the all-electric range of the PHEV and thus the batteries are completely depleted when the drivers arrive at home.

To study the worst possible scenario, the simulations are repeated with BEVs with 160 km range. In these cases, drivers use only electricity throughout the day and get back home with a state of charge greater than zero.

Two different charging scenarios are considered: 1) *uncontrolled charging* where charging starts when the driver gets home and stops when the battery is fully charged, and 2) *off-peak* charging where the charging is moved to off-peak hours. Two charging levels, Level 1 at 1.44 kW and Level 2 at 7.2 kW are also studied. In the *off-peak charging* scenario, the preferred charging hours are from midnight to 6 am when the base load electrical demand is at a minimum (Fig. 3) and the charging is staggered in a way such that the load on the transformer during that window is minimized. With Level 1 charging this window is not long enough for the vehicles to be fully charged and thus some vehicles must begin charging before midnight.

Table 1
Times that the vehicles are parked at home and the electricity required to fully charge the battery for 10 households.

	Leaving home	Returning home	Consumption needed from the grid (kWh)	
			PHEV	BEV
Driver1	7:13 AM	7:18 PM	12.76	13.57
Driver2	6:49 AM	5:54 PM	12.76	19.81
Driver3	8:10 AM	5:30 PM	8.07	8.07
Driver4	7:00 AM	6:40 PM	12.76	14.10
Driver5	7:40 AM	5:45 PM	5.87	5.87
Driver6	6:30 AM	3:50 PM	11.00	11.00
Driver7	6:00 AM	6:00 PM	12.76	14.69
Driver8	7:50 AM	7:00 PM	12.76	12.88
Driver9	8:40 AM	7:30 PM	12.76	22.38
Driver10	7:50 AM	6:20 PM	12.76	16.51

The charging profiles of all ten vehicles are shown in Fig. 4 for various scenarios. Since the power factor of the vehicles connected to the grid is nearly unity (this has been proved by measurement by the authors and it is also a mandatory condition for loads connecting to the grid) the load on the transformer would be the sum of the base load and the vehicles' load. The transformer loads for the Level 2 charging scenarios of BEVs are shown in Fig. 5. The description of various cases, peak load on the transformer, and the time of the peak load are shown in Table 2. It can be seen that for both charging levels, *off-peak charging* will result in a smaller peak compared to the *uncontrolled charging*. Furthermore, by *off-peak charging* with Level 1, the peak load on the transformer is kept almost unchanged compared to the *basecase*.

It should be mentioned that with Level 1 charging of BEVs (both *uncontrolled* and *off-peak*) drivers 2 and 9 cannot charge their batteries fully, simply because the dwelling time is not sufficient. They leave the house with 94% and 85% state of charge, respectively which is enough for their next day travel; however, several days of similar driving and recharging is not sustainable.

2.2. Thermal model

The most important factor in transformer loss of life is the thermal stress that will result in the degradation of the winding insulation. This degradation is directly affected by the highest temperature observed in the winding, known as the hot spot temperature (HST) [36–40]. The temperature rise of the winding hot spot is a function of transformer loading, and thus the winding deteriorates as a function of time and temperature. In order to calculate the loss of life of the transformer due to the loading, the hot spot temperature must first be calculated. For an oil-immersed transformer the HST is calculated from Equation (1).

$$\theta_{\mathrm{HST}} = \theta_{\mathrm{amb}} + \Delta\theta_{\mathrm{Oil}} + \Delta\theta_{\mathrm{HST}} \tag{1}$$

Temperature rise of the oil over ambient ($\Delta\theta_{\mathrm{oil}}$) for each time step can be calculated from Equations (2)–(4).

$$\Delta\theta_{\mathrm{Oil}} = (\Delta\theta_{\mathrm{Oil},U} - \Delta\theta_{\mathrm{Oil},i})\left\{1 - \exp\left(\frac{-t}{\tau_{\mathrm{oil}}}\right)\right\} + \Delta\theta_{\mathrm{Oil},i} \tag{2}$$

$$\Delta\theta_{\mathrm{Oil},i} = \Delta\theta_{\mathrm{Oil},R}\left[\frac{\left(K_i^2 R + 1\right)}{R+1}\right]^n \tag{3}$$

$$\Delta\theta_{\mathrm{Oil},U} = \Delta\theta_{\mathrm{Oil},R}\left[\frac{\left(K_U^2 R + 1\right)}{R+1}\right]^n \tag{4}$$

Similarly the hot spot temperature rise over the oil can be calculated from Equations (5)–(7).

$$\Delta\theta_{\mathrm{HST}} = (\Delta\theta_{\mathrm{HST},U} - \Delta\theta_{\mathrm{HST},i})\left\{1 - \exp\left(\frac{-t}{\tau_w}\right)\right\} + \Delta\theta_{\mathrm{HST},i} \tag{5}$$

$$\Delta\theta_{\mathrm{HST},i} = \Delta\theta_{\mathrm{HST},R} K_i^{2m} \tag{6}$$

$$\Delta\theta_{\mathrm{HST},U} = \Delta\theta_{\mathrm{HST},R} K_U^{2m} \tag{7}$$

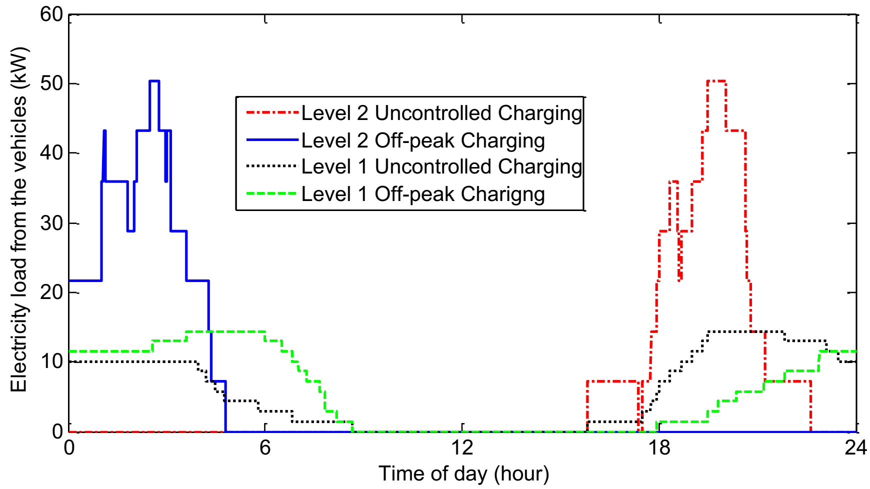

Fig. 4. Electricity demand of BEVs for various charging scenarios (cases 6–9).

It should be noted that in Equations (2) and (5), t is the time elapsed after the last load change. Therefore, if the transformer load at a time step is the same as the load at the previous time, t would be the time accrued since the last change in the load. The transformer parameters in the previous equations are replaced with values corresponding to a typical distribution transformer that were obtained by conducting an extensive survey of the literature [23,38,41–46]. The values are shown in Table 3.

2.3. Transformer life loss

As mentioned previously, the hot spot temperature is believed to indicate the loss of life of the transformer insulation. Empirical formulas suggest that the insulation degradation with time and temperature follows the Arrhenius reaction rate theory [36,38]. IEEE C57.91 standard recommends the use of Equation (8) to calculate the aging acceleration factor. The reference temperature is assumed to be 110 °C (at rated power) for which the aging acceleration factor is unity. For temperatures over 110 °C, the aging acceleration factor is greater than 1 showing that the aging accelerates as the temperature rises.

$$\mathrm{AAF} = \exp\left(\frac{15000}{383} - \frac{15000}{\theta_{\mathrm{HST}} + 273}\right) \tag{8}$$

For each time step (15 s) the aging acceleration factor is calculated and then the equivalent aging factor for the given time period (here 24 h) is calculated using Equation (9).

$$\mathrm{EAF} = \left(\sum_{i=1}^{N} \mathrm{AAF}_i \, \Delta t_i\right) \bigg/ \sum_{i=1}^{N} \Delta t_i \tag{9}$$

To calculate the percentage loss of life during a 24 h operation, the normal life of the insulation is chosen as 180,000 h [36,46] and the loss of life percentage is calculated from Equation (10).

$$\mathrm{LOL\%} = \mathrm{EAF} \times 24 \times 100/180,000 \tag{10}$$

3. Results

The profiles of the household electricity load and vehicle load simulations can be seen in Figs. 2–5. These results depend on the

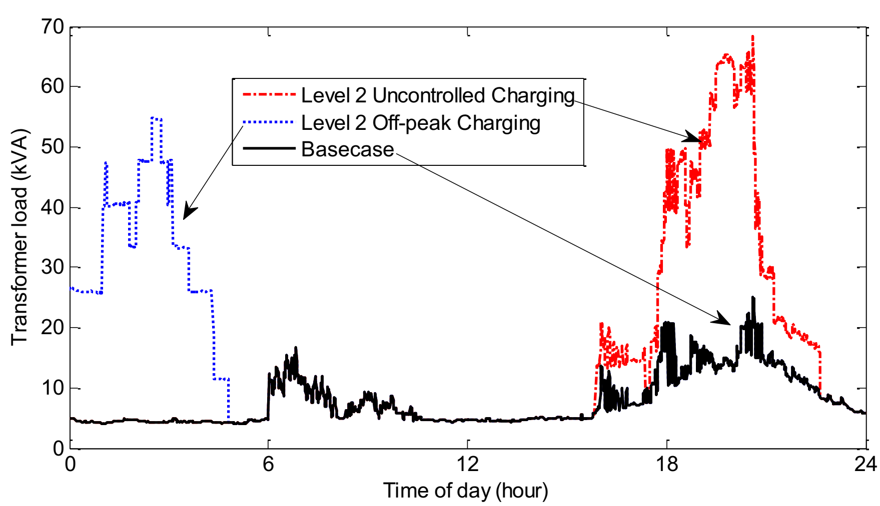

Fig. 5. Transformer load (kVA) for the Level 2 *uncontrolled* and *off-peak charging* of BEVs (cases 7 and 9).

Table 2
Case descriptions and peak load on the transformer.

Case number	Case description		Maximum transformer load (kVA)	Time at which the maximum occurs
	Vehicle	Charging profile		
1	Basecase		25.06	8:36 PM
2	PHEV	Level 1 Uncontrolled	39.46	8:36 PM
3	PHEV	Level 2 Uncontrolled	64.26	7:40 PM
4	PHEV	Level 1 Off-peak	26.94	6:47 AM
5	PHEV	Level 2 Off-peak	40.85	1:43 AM
6	BEV	Level 1 Uncontrolled	39.46	8:36 PM
7	BEV	Level 2 Uncontrolled	68.26	8:36 PM
8	BEV	Level 1 Off-peak	30.81	8:36 PM
9	BEV	Level 2 Off-peak	54.74	2:32 AM

Table 3
Parameters of a typical transformer.

R	τ_{oil}	τ_w	$\Delta\theta_{\text{oil},R}$	$\Delta\theta_{\text{HST},R}$	m	n
5	3 h	5 min	55 °C	25 °C	0.8	0.8

household daily electricity demand profiles, vehicle type, and the charging scenario of the vehicles, and not on the transformer size. However, as discussed in the previous section, the hot spot temperature equations include variable K which is the ratio of the transformer load to its rated power. Therefore, the size of the transformer must be known to carry out the simulations.

For number of residential customers between 6 and 15 it is common to use one of these three transformers sizes: 37.5 kVA, 50 kVA, and 75 kVA. Taking into account that distribution transformers have an average load of 15–40% of their rating [47–49], the 37.5 kVA and 50 kVA transformers appear suitable for the simulated load with average load of 20.7 and 15.5% of their ratings, respectively. All nine cases introduced in Table 2 are studied once for a 37.5 kVA transformer and again for a 50 kVA transformer (eighteen different runs overall).

Before presenting the results, it must be noted that transformers are able to handle loads above their rated capacity for a short time and an overload does not necessarily mean that the transformer will fail. IEEE C.57.91 standard recommends maximum limits for the load, oil temperature, and winding hot spot temperature as shown in Table 4. If any one of these three limits is reached, the transformer is highly likely to fail.

3.1. Load factor (K)

The load factor (K) does not reach its limit of 2 in any of the cases studied for either of the transformers. Fig. 6 shows the load factors of a 37.5 kVA transformer for the case with uncontrolled Level 2 charging of BEVs (worst case). This scenario results in the highest load factors observed and still does not quite reach the maximum limit.

3.2. Hot spot temperature

In order to calculate the hot spot temperature, the ambient temperature of constant 30 °C is assumed throughout the day. This is a conservative assumption for a very hot day since the ambient temperature generally falls at night. Fig. 7 shows the hot spot temperature results for a 37.5 kVA transformer under *Basecase* conditions. Figs. 8 and 9 show hot spot temperatures of the two transformers for Level 1 charging of BEVs with both *uncontrolled* and *off-peak* profiles. As can be seen from these figures with Level 1 charging, none of the scenarios result in excessive temperatures.

Table 4
Recommended limits of temperature and loading for a distribution transformer [36].

Oil temperature	110 °C
Winding hot spot temperature	180 °C
Short time loading (30 min or less)	200%

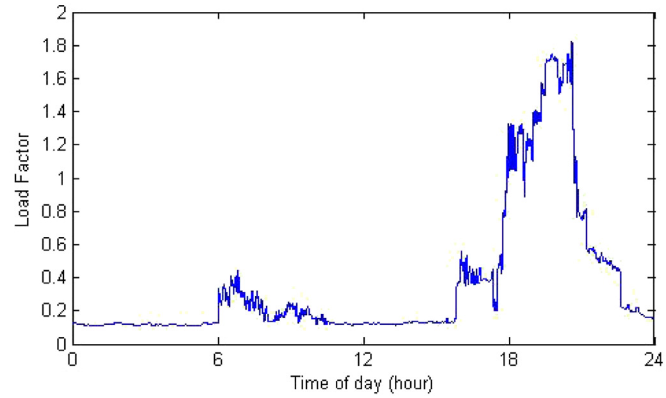

Fig. 6. Load factor corresponding to a 37.5 kVA transformer with Level 2 *uncontrolled* charging of BEVs (case 7).

Figs. 10 and 11 show the hot spot temperature for Level 2 charging of the BEVs. It can be seen in Fig. 10 that for some time the hot spot temperature exceeds the 180 °C limit for a 37.5 kVA transformer. The results for all the nine cases are summarized in Table 5 for both transformer sizes. In cases 3 and 7, the 37.5 kVA transformer is operating at a temperature higher than the limit for 25 min and 1 h and 17 min, respectively, which can result in failure of the transformer. It can be concluded that only for the *uncontrolled charging* at Level 2, there is a chance that a 37.5 kVA transformer will fail and the service would be disrupted.

The simulations were carried out for the oil temperature and the same results were reached; only *uncontrolled charging* at Level 2 might result in a transformer failure if the transformer had not been adequately overdesigned (here a 37.5 kVA and smaller).

Another interesting result is shown in the plots of the hot spot temperature versus load factor. For all the cases and both transformers, these plots can be estimated with the same parabolic function as shown in Fig. 12. This plot can be used to estimate the hot spot temperate without performing all the simulations. The accuracy of using this plot improves at lower load factors.

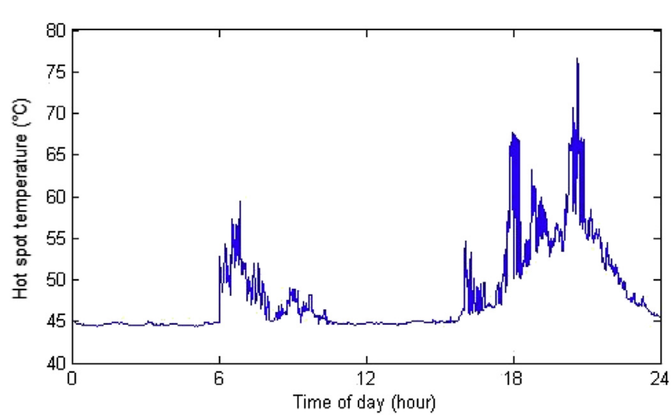

Fig. 7. Hot spot temperature of a 37.5 kVA transformer for the *Basecase*.

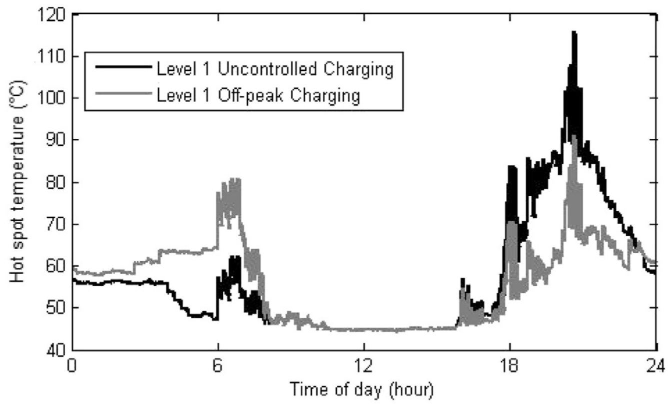

Fig. 8. Hot spot temperature of a 37.5 kVA transformer with Level 1 charging of BEVs (case 6 and 8).

3.3. Loss of life

As previously discussed, life of a transformer is the calculated life of the winding insulation which is a function of time and temperature. Equations in Section 2.2 are used to calculate the aging acceleration factor, equivalent aging factor, and loss of life percentage for all the cases for both 37.5 and 50 kVA transformers. In Fig. 13, the aging acceleration factor during the day for a 37.5 kVA transformer with Level 1 charging for both *uncontrolled* and *off-peak* charging of BEVs are shown. This figure shows that off-peak charging significantly reduces the aging rate of the distribution transformer and thus increases the reliability of grid operations.

Equivalent aging factors and loss of life percentage for a 24 h period for all the cases are shown in Table 6. As seen from the table, the addition of PEVs results in loss of life of the transformer. With Level 1 charging, this impact is very small; however, in the case of Level 2 *uncontrolled charging*, a small transformer (37.5 kVA) ages 26 times faster in a 24 h period with the addition of PHEVs and 121 times faster with BEVs. This might require that the transformer be replaced sooner than originally planned, and maintenance be scheduled more frequently to prevent the failure of the transformer. These results might be a little discouraging; however, by comparing case 3 with 5, and case 7 with 9 from Table 5, it can be seen that the negative impact of PEVs on the distribution transformer can be mitigated by smart charging and that the addition of significant number of these vehicles to a neighborhood requires advance planning and integration of smart technologies into the grid.

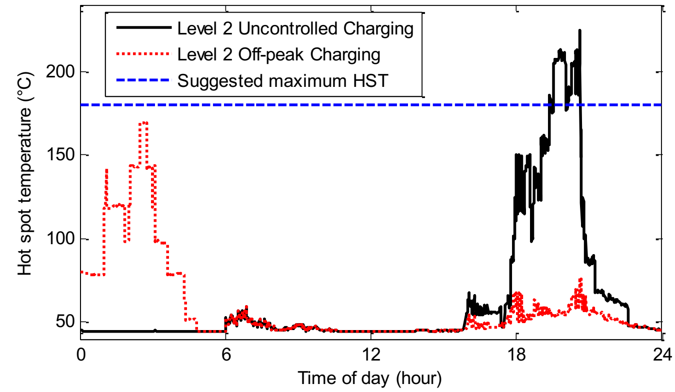

Fig. 10. Hot spot temperature of a 37.5 kVA transformer with Level 2 charging of BEVs (cases 7 and 9).

To summarize, as expected, the addition of the PEVs affects the life of the distribution transformer. However, this effect is minimal if the transformer had been properly designed for both charging levels. For smaller transformers, the charging profile becomes crucially important since, in the case of Level 2 charging there is a chance of catastrophic transformer failure.

4. Discussion

In this study, the electricity demand of a Southern California neighborhood comprised of ten households is modeled using a statistical Monte Carlo method based on measured electricity demand and power factors. Each household is then assumed to house a PEV. The electricity required to fully charge the vehicle's battery is modeled based on real data of home arrival and departure times and driving patterns during a weekday, and vehicle type. The distribution transformer load serving this neighborhood is calculated, and a transformer thermal model is developed to track the hot spot temperature of the transformer for different cases and charging scenarios.

Addition of multiple PEVs in a neighborhood will result in faster aging of the transformer's windings, as any increase in electricity demand would do. This increase in aging rate appears to be acceptable when the vehicles are charged at Level 1, even with *uncontrolled charging* where the majority of the charging coincides with daily peak demand. Charging timing and profile are especially important when Level 2 charging is used since *uncontrolled charging* will result in very high aging rates and possibly even transformer failure if a transformer with a smaller rating had been chosen for the circuit. Overall, it was shown that the addition of a

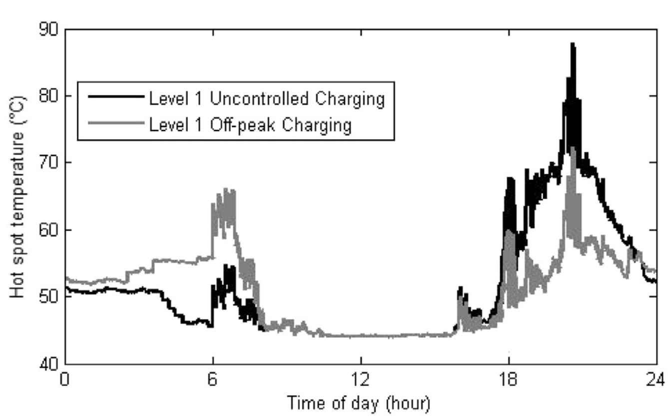

Fig. 9. Hot spot temperature of a 50 kVA transformer with Level 1 charging of BEVs (cases 6 and 8).

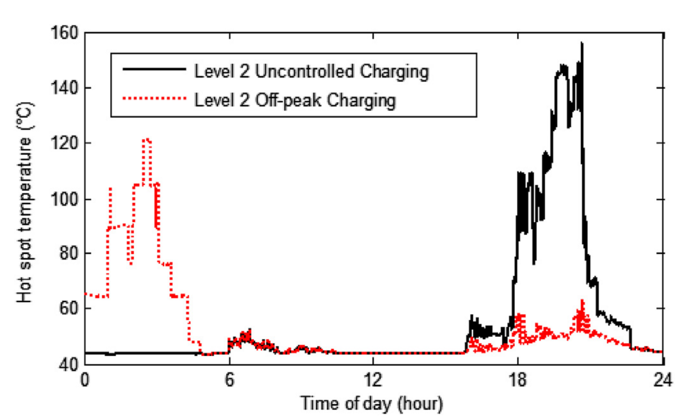

Fig. 11. Hot spot temperature of a 50 kVA transformer with Level 2 charging of BEVs (case 7 and 9).

Table 5
Summary of hot spot temperature results.

	37.5 kVA		50 kVA	
	Average HST (°C)	Highest HST (°C)	Average HST (°C)	Highest HST (°C)
Case 1	48.19	76.63	46.16	63.41
Case 2	55.95	115.99	50.87	87.77
Case 3	60.17	207.76	53.55	145.14
Case 4	54.55	80.92	49.99	66.05
Case 5	56.62	120.41	51.30	90.52
Case 6	56.89	115.99	51.43	87.77
Case 7	63.18	225.04	55.42	155.98
Case 8	56.07	90.97	50.91	72.25
Case 9	59.64	169.35	53.17	121.08

significant number of PEVs is likely manageable for the distribution circuit and transformer, and with the use of smart charging and load management, the negative effects can be minimal.

Following are the conclusions of this research:

- Catastrophic failure of distribution transformers due to vehicle charging is unlikely, even with the addition of PEVs to every house in a neighborhood.

Among all the eighteen cases studied, only *uncontrolled charging* of all vehicles at Level 2 resulted in a possible transformer failure when a smaller transformer was chosen. It should be mentioned that distribution transformers are generally chosen conservatively by utilities, and that the 50 kVA transformers are the most common size for the circuits studied in this paper, and thus the case of the failure is highly unlikely.

- Level 1 charging, even with an uncontrolled profile, has little effect on the transformer life time.

Comparing the results of the *Basecase* with the cases including vehicles with Level 1 charging indicate a loss of life; however, in these cases the loss of life during a 24 h period is very small and has little impact on real life operations.

- *Off-peak charging* results in prolonging the transformer's life and reducing the chance of premature failure to nearly zero.

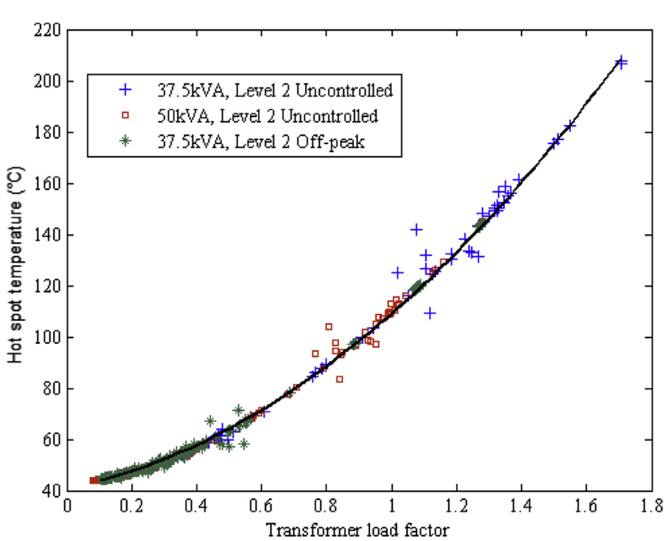

Fig. 12. Hot spot temperature vs. load factor.

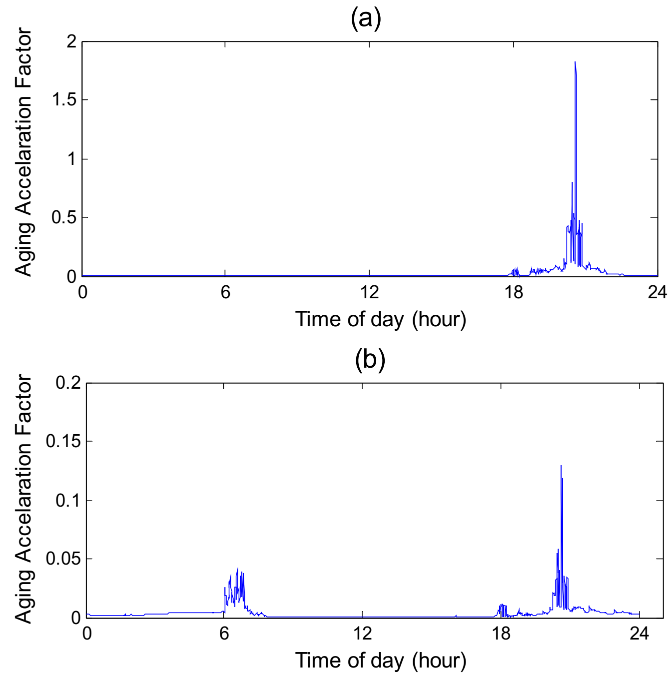

Fig. 13. Aging acceleration factor corresponding to a 37.5 kVA transformer with Level 1 charging of BEVs (a) *Uncontrolled* (b)*Off-peak*.

Table 6
Equivalent aging factor and loss of life percentage for transformers for a period of 24 h.

	37.5 kVA		50 kVA	
	EAF	LOL%	EAF	LOL%
Case 1	8.28E-04	1.10E-05	4.56E-04	6.08E-06
Case 2	0.0203	2.71E-04	0.0023	3.09E-05
Case 3	26.9392	0.3592	0.3099	0.0041
Case 4	2.60E-03	3.46E-05	8.99E-04	1.20E-05
Case 5	0.1071	1.1E-05	6.1E-03	8.13E-05
Case 6	0.0204	2.73E-04	2.36E-02	3.15E-05
Case 7	121.449	1.6193	1.1741	0.0157
Case 8	3.83E-03	5.09E-05	1.11E-03	1.48E-05
Case 9	2.9730	0.0396	0.0578	7.72E-04

In all the studied cases, *off-peak charging* showed significant advantage to the *uncontrolled charging* in terms of winding hot spot temperature and transformer loss of life.

- Smart charging and load management will become crucially important for transformers that have been primarily chosen to operate at higher load factors.

These transformers are in danger of failure when vehicles are charged without any management, especially at Level 2 and are required to be monitored closely in order to prevent such failures.

- Plug-in vehicles' electricity demand, although comparable to that of an entire additional household, is manageable for the distribution transformer even if multiple vehicles exist on the same residential circuit.

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